CHAPTER 3

POWER CONDITIONING

3-1. Automated data processing (ADP) power requirements

Typical applications of electronic equipment are in mainframe and distributed data processing computers and their peripherals, customer-owned telephone switching systems, and increasingly complex electronic industrial control equipment. Faulty performance of these units can cause inconvenient, expensive, and even dangerous situations. These electronic circuits in this equipment operate on dc power. The source of this power is an internal dc power supply which converts (rectifies) the ac power furnished by an electric utility to the various dc voltage levels required by the electronic equipment. Internal dc power supplies are designed to isolate the electronic equipment from moderate disturbances on the ac power lines. But the fact is that frequently types and levels of power line disturbances are encountered which pass, little altered, through internal power supplies. This causes aberrations in the dc voltage levels, which can result in everything from faulty operation to complete shutdown or failure of the electronic equipment. One of the major problems when electronic equipment performs incorrectly or shuts down unexpectedly is locating the source of the trouble. Scrambled data in a recirculating memory can, for example, look like a hardware or software failure on the surface whereas it might actually have been caused by an intermittent blip on the power line. It is, therefore, important that a user know something about the kinds of disturbances that appear on his power line and how often they occur. This does away with much of the finger pointing by the user and various service personnel when a problem does arise, and at the same time permits steps to be taken to prevent these disturbances from reaching the dc power supplies. The proper choice of equipment designed to isolate the power supply from line disturbances is wholly contingent on the precise types of power line disturbances expected, the estimated frequency of occurrence, and the importance to the user of keeping the electronic equipment on line.

a. Electronic equipment used in computers operates on dc power equivalent to that obtained from an ordinary battery. It is a single-polarity (either plus or minus) and is derived by converting or rectifying the ac power supplied by a utility. Typical dc levels required by solid-state electronic equipment are plus or minus 5, 12, 15, and 24 volts. Power line disturbances, which pass through a power supply, can cause dc voltage levels to rise or fall slowly or rapidly, exhibit positive or negative spikes, or even drop to zero. Any of these occurrences can cause faulty equipment performance, system shutdown, or even damage to sensitive electronic components.

b. The ac power generated by electrical utilities is characterized by alternating back and forth between equal positive and negative voltage levels along a pure sinewave wave form. Because of the sinewave characteristics there are various ways of describing ac power. The nominal 120 volts from an outlet is actually the effective or root mean square (RMS) voltage of the ac wave. It is equivalent to 120 volts dc when supplying a pure resistance load such as an incandescent light bulb – thus the name effective. The negative and positive peak voltages are equal to 1.414 times the RMS voltage, while the average one-cycle voltage is equal to 0.637 times the positive or negative peak voltage. Thus for our 120-volt outlets, the peak voltages are equal to 120 times 1.414 or 170 volts, while the average voltage equals 170 times 0.637 or 108 volts. In turn, of course, the RMS voltage is equal to 0.707 times the peak voltage. In the United States, ac power is generated at a frequency of 60 hertz or cycles per second (in other countries 50 hertz power is common). This means there are 60 full sinewaves per second so that a cycle is 16.7 milliseconds long.

(1) Utilities supply residential structures and commercial and industrial offices with single-phase ac power. Usually there are three-wire systems with two "hot" conductors and a neutral. The neutral is grounded at the service entrance (normally to a water pipe) and this ground lead or a ground connection is carried throughout the system. One hot lead, the neutral, and the ground connection are carried to the standard 120 volt outlets. Under proper operating conditions only the hot and neutral leads carry current; the ground connection is for safety purposes. If there should be an insulation breakdown in the energized equipment, the ground connection will drain the current back to ground, thus preventing personnel exposure to 120 volts.

(2) For higher powered equipment, such as ranges, air conditioners, electric heating, clothes dryers, and some office equipment, the two hot conductors and ground are wired to special outlets. This yields 240 volts and halves the current that would be required if the same equipment was designed to operate on 120 volts.

(3) For large electric power users, utilities generate and transmit three-phase ac power in which the three phases are time phased by one-third cycle, effectively producing three ac wave forms. Three-phase power is less expensive to transmit, simpler to rectify into low-ripple ac voltage, and three-phase ac motors are simpler and operate more smoothly than single-phase motors. The single-phase residential power mentioned above is obtained by tapping off one phase of a three-phase transmission line.

(4) Every industrial facility and most large computer installations are supplied with three-phase power. The most popular configurations for supplying this three-phase power are the four-wire "wye" with ground and the ungrounded and grounded "delta." Wye circuits can usually handle either 480 volt or 208 volt three-phase loads and 277 volt or 120 volt single-phase loads. The 120 volt level is, of course, that obtained from the standard ac outlet, whereas 277 volts is a popular level for fluorescent lamp fixtures. Both types of delta circuits normally supply either 480 volt or 240 volt three-phase loads.

3-2. Power line disturbances

All of these types of ac circuits are susceptible to line disturbances which may either be introduced via the utility's transmission lines or generated internally within the user's own facility. Breaker tripping and reclosure for fault clearance, random switching of heavy loads, lightning strikes, noise, motor controllers, and an endless number of similar occurrences can and will introduce ac line disturbances about which the utility can do little. With the exception of frequency variations, all power line disturbances are voltage phenomena, with the type of disturbance and the means of compensating for it depending on the magnitude and time period of the voltage excursion beyond a nominal voltage band. Fluctuations of the RMS voltage value over an appreciable time interval are known as undervoltages or overvoltages, shorter term variations are called sags or swells, and spikes or transients of very short duration and considerable peak magnitude are known as impulses. Dropouts or line interruptions are where the line voltage goes to zero, a situation that can exist for any time period.

a. Any RMS voltage fluctuation which exceeds allowable limits for more than 1 minute is classed as an undervoltage or overvoltage.

(1) Undervoltage situations are normally caused by purposeful utility "brownouts" and/or line overloading either within the same facility or by neighboring facilities on the same transmission line. Utilities cause brownouts by deliberately dropping the voltage by 3, 5, or even 8 percent to extend system capability, particularly on hot days with heavy air-conditioning loads and limited reserve.

(2) Overvoltage is caused by poor line regulation by a utility or by lighter than expected loads on the line. If, for example, an emergency forced several neighboring plants to shut down during the normal working day, transmission line voltage would undoubtedly rise until the utility could bring it back under control.

(3) Overvoltage causes electronic equipment to run hot, stressing components and possibly prompting immediate or incipient failures. Equipment shutdown may also occur if the heat dissipation forces the enclosure to reach unsafe high temperatures and a thermal limit trips. Normal utility voltage variations, plus internal facility feeder line voltage drops and the ever present possibility of brownouts in certain sections of the country, make undervoltage situations fairly common. If the voltage drops sufficiently, all kinds of erratic performance can be expected as electronic equipment nears the point where it will stop operating completely. Also, motor loads draw more current and run hotter and less efficiently under low voltage conditions.

b. Sags and swells are short-term special cases of undervoltage and overvoltage conditions where the voltage fluctuation exceeds the allowable limit for at least some significant portion of one cycle (say 10 milliseconds) and reenters the limit band within 1 minute. Because sags and swells are transitory conditions caused by momentary occurrences, they usually exhibit larger voltage excursions than longer term undervoltages and overvoltages.

(1) Swells look the same as sags except that the voltage exceeds the upper limits that are usually established at 10 percent. Sags are most commonly caused by switching on to the line heavy loads such as large motors, electric furnaces, substantial air-conditioning capacity, etc. Such loads draw heavy inrush currents, which drop the voltage for short periods and line voltage regulation typically takes a definite period to recover from such heavy loads. Swells are frequently caused by the reverse – the disconnecting of heavy loads from the line with the accompanying voltage increases.

(2) If sags or swells have sufficient magnitude to be reflected through the internal dc power supplies, they can play havoc with the performance of sensitive electronic equipment. For example, equipment designed to initialize upon startup may re-initialize after a severe sag – it confuses the sag with the turn off and turn on of power. And much electronic equipment shuts down and stays shut down if the voltage drops below a limit for more than a few milliseconds. Particularly disruptive situations can occur if part of the equipment in an integrated system starts up after recovery from a sag and the balance of the equipment does not.

c. Impulses are deviations from the ideal ac sinewave having very short duration compared with one cycle – typically from a fraction of a microsecond to a very few milliseconds. Their forms range from single pulses with extremely short rise time and gradual decay to oscillatory disturbances persisting for five to ten oscillations within a gradually decaying envelope. They may either increase or decrease the instantaneous amplitude of the sinewave described as a "spike" or "notch," respectively.

(1) Impulses can range in magnitude from a fraction of peak voltage up to hundreds or thousands of volts and by far cause the largest voltage swings of any types of line disturbances.

The proper way to examine an impulse disturbance is to filter out the sinewave. If any impulse spike with a magnitude of 500 volts occurred at the top of a nominal 120 volt sinewave, then the actual voltage impressed on the load would be 500 volts plus the peak instantaneous voltage of 170 volts or 670 volts.

(2) Two other measures of an impulse disturbance are impulse duration and impulse strength. Impulse strength is defined as the volt-second area under the impulse curve. It is clear that impulse strength and impulse duration are related and either adds a significant measure to the knowledge of the problems a transient can cause beyond the straightforward measurement of impulse magnitude by itself.

(3) It is also important to know the direction or source of an impulse. Did it occur at the source of power via the utility power feeder or was it generated in the electronic equipment? Either is possible, and of course, the solutions to the two problems are radically different.

(4) There are two types of impulses: common-mode transients where the voltages to ground of the ac power line phases rise and fall together, and normal-mode transients where the phase-to-ground voltages vary from phase to phase. Common-mode impulses are caused by such things as lightning and utility breaker tripping and reclosure, usually resulting in single spikes or notches on the sinewave. In contrast, normal-mode impulses are typically the result of connecting or disconnecting heavy loads or power factor compensating capacitors. These impulses exhibit decaying oscillatory characteristics with frequencies up to and above 5 kilohertz (kHz). It is important to know the type of impulse since the means of suppressing them are different.

(5) Impulses are the most insidious type of power line disturbance. They occur without any indication at all to operating personnel, and if not suppressed can cause scrambled data transmission or memory data resulting from bit changes, over-stressed components, or even component failure.

d. Loss of total power to zero voltage can occur for any time period from a portion of a cycle on up to hours or even days. Very short-term dropouts are frequently caused by utility breakers tripping to clear a fault and then reclosing automatically, while long-term line interruptions can result from any serious utility problem – power lines felled by a storm or fires in substations are typical. Most computers and sensitive electronic equipment, which depend on digital data manipulation, will shut down automatically if a power dropout exceeds a very few milliseconds.

e. Frequency deviation is seldom a problem with utility-supplied power in the United States. Frequency rarely varies more than 0.5 hertz from 60 hertz (a common computer specification) and is always averaged out over a 24-hour period because of the number of clocks and other time-based devices, which depend on constant frequency for accuracy. However, if power is generated locally by a private power plant or by motor-generator (M-G) sets or diesel or gas turbine engines, frequency can wander over a 10 hertz band from 55 to 65 hertz. Frequency shifts of this magnitude can cause problems with time-based equipment or frequency-sensitive circuits.

3-3. Acceptable limits for ac power

Although there are no industry standards to define "acceptable" ac power, the Information Technology Industry Council (ITI) has issued a guideline (shown in appendix B) that describes the ac input voltage envelope which typically can be tolerated by information technology equipment (ITE) . The various sags, swells, undervoltages, overvoltages, and impulses exhibited by a power line can be classified as acceptable or unacceptable based on whether they fall within or without the dashed-line boundaries. In these guidelines, long-term overvoltages or undervoltages which deviate from the nominal voltage by more than +10 percent or -20 percent for longer than 500 milliseconds (30 cycles) can be expected to cause problems. Any swell or sag, which exceeds +20 percent or –30 percent of the nominal voltage for more than 20 milliseconds (1.2 cycles), is apt to cause faulty operation of ITE. The impulse band is more difficult to define because of the frequent high magnitude of the transients, but, generally speaking, impulses greater than the nominal peak sinewave voltage can degrade a system's operation. If monitored power line disturbances fall outside these boundaries, particularly during pre-installation site inspection, a careful analysis may avoid future problems.

3-4. ADP protective equipment

Although it is difficult to make any generalizations concerning the benefits that accrue from the use of line protective equipment, it has been estimated that clean power versus that taken directly from the "average" power line reduces load equipment outages by 40 percent and maintenance costs by 25 percent. The choice to use protective equipment is both an economic and technical consideration. The wide range of power line conditioning and isolating equipment varies greatly in price and in the types of disturbances it will protect against. Less expensive protective equipment may not provide much improvement and costly equipment for every conceivable power line problem may not be economically justifiable.

a. Once the profile and estimated frequency of occurrence of line disturbances via power line monitoring is determined, an economic analysis should be performed. This analysis should include a complete life cycle cost analysis associated with purchasing and operating the protective equipment, the costs incurred as a result of load equipment outages, faulty performance, hardware damage, and any other anomaly that may occur for various degrees of power line protection.

(1) Costs to consider are the initial purchase price of line conditioning or isolating equipment, installation costs, and operating costs. Within these, consideration should be made for site preparation, equipment operating efficiency, and maintenance requirements.

(2) Site selection and preparation may be a major contributor since some line conditioning equipment may require special space and site preparation. In new building construction, space limitations may not be a problem, but space may be a major factor when a large computer installation in an existing facility requires retrofitting.

b. Special factors requiring consideration prior to selection of protective equipment are as follows.

(1) Transformer hum or rotating equipment noise may require a sound baffled enclosure or location away from occupied areas.

(2) Large battery banks in some uninterruptible power supply (UPS) systems are heavy and require substantial surrounding space to permit proper maintenance. Certain battery types also generate explosive fumes that an isolated space with forced ventilation and extra reinforcing because of heavy floor loading.

(3) Environmental conditions must also be considered if the load protective equipment is located in the same space as the computer or other electronic load devices. The line conditioning and isolation equipment generates heat, which may require additional air-conditioning capacity.

(4) Equipment efficiencies must also be considered in the cost. No load protective equipment is 100 percent efficient, and efficiencies may range from as low as 50 percent to a high 96 percent. This electrical energy incurs a cost with the efficiency of some types of protective equipment decreasing with time so this continuing cost may increase as the equipment ages. Obtain efficiency rates from the equipment supplier for the actual conditions under which the equipment will be operating.

(5) Equipment maintenance is a continuing expense, which must also be considered. All electronic systems require periodic inspection and will fail from time to time. Modular plug-in construction and diagnostic aids speed troubleshooting and repair, but parts and labor still cost money. Batteries require periodic monitoring of electrolyte and terminal cleaning, and all rotating equipment needs, at minimum, regular bearing inspection and occasional bearing replacement. Backup engine-driven alternator sets have particularly high maintenance costs.

c. Isolation transformers used for protective devices are primarily intended to attenuate common-mode impulses. Some types also provide limited attenuation of normal mode impulses. Isolation transformers perform no voltage regulating function. Sags, swells, undervoltages, or overvoltages will be reproduced faithfully on the transformer secondary. If the power line voltage is consistently stable and high frequency impulses or noise is the only problem, then a suitable isolation transformer may eliminate your power line disturbance difficulties.

(1) While a standard transformer has no dc connection between primary and secondary, the windings are ac coupled through an infinite number of coupling capacitances. At high noise frequencies, these capacitances have relatively low impedance and transfer the noise directly from primary to secondary. Thus a standard transformer has practically no ability to attenuate impulse noise but instead passes it right through.

(2) The basic isolation transformer helps this somewhat by inserting an aluminum foil electrostatic Faraday shield between the primary and secondary windings. While this shield does not completely eliminate this coupling capacitance, it shunts a lot of it to ground and thus minimizes the transformer's ability to transfer common mode impulses. Power line noise on the primary is considerably attenuated by the time it reaches the secondary.

(3) The ultimate isolation transformer (variously called high, super, ultra, etc., by different suppliers) further reduces this coupling capacitance with box electrostatic shields around the primary and secondary windings. Capacitances between the windings and the frame and windings are broken up into smaller series capacitances and shunted to ground, thus minimizing input-to-output capacitance of 0.001 pico-farads, and the better ones are as low as 0.0005 pico-farads. This very low level of coupling capacitance effectively prevents common mode impulses on the power line from reaching the load.

(4) Attenuation capability for a top quality isolation transformer is expressed in decibels (dB), a shorthand way of indicating attenuation ratios. The higher the dB rating the isolation transformer has the better the noise attenuation. Well designed dc power supplies exhibit considerable normal-mode noise attenuating capability.

(5) High quality isolation transformers are available in sizes ranging from 125 VA single-phase to 130 kVA three-phase. Isolation transformers with somewhat lower levels of impulse attenuation are also available . There are many different suppliers with various quality level transformers so almost any specific performance requirement can be satisfied.

d. Line voltage regulators do exactly what the name implies – their purpose is to maintain reasonably constant output voltage to the load in the face of variations in power line voltage. There are many different ways of accomplishing this and among the basic types there are innumerable variations, all with their own advantages and limitations. The following covers one or two popular or generic versions of five basic types of voltage regulators.

(1) Most line regulators will correct utility voltage sags and swells of 15 percent to output voltages to the load ranging from ±3 to ±7 percent of nominal. Many will bring extreme utility sags in the area of 20 to 30 percent, back to ±7 to ±10 percent of the nominal output voltage. Some things to consider when picking a line voltage regulator are cost, speed of response, output impedance, audible noise, efficiency at part and full load, sensitivity to load power factor and unbalanced three-phase loads, and harmonic distortion.

(2) A few types of line regulators can attenuate impulses to a modest degree, but most perform the regulation function only and pass impulses right through. In fact, some types may create additional impulse noise by internal switching.

(3) There are two types of motor-actuated regulators, the motor-driven brush type and the induction regulator type. The motor-driven brush type moves across many taps on an autotransformer, causing the series transformer to buck or boost the voltage to the load. The same function is performed by an induction regulator where rotating the regulator one direction or the other varies the magnetic coupling and raises or lowers the output voltage.

(4) Motor-actuated voltage regulators are generally inexpensive and can handle heavy loads, but they are slow in response and can only correct for gradual voltage changes. In addition, their electro-mechanical parts require substantial maintenance and output impedance is high. They are not often used with critical and sensitive electronic equipment.

(5) The saturable reactor regulator controls output voltage by varying the impedance of the saturable reactor winding in series with a step-up autotransformer. These regulators are relatively inexpensive, and have a wide load range, low maintenance requirements, and yield fair normal-mode impulse protection. However, the disadvantages often outweigh these plus factors. Sag/swell response is sluggish (in the range of 5 to 10 cycles), output impedance is high (as much as 30 percent of the load impedance), and they are sensitive to lagging load power factor.

(6) The ferro-resonant transformer voltage regulator is one of the more popular regulators, especially in the lower size ranges of 0.5 to 2 kVA. The ferro-resonant transformer core structure is designed so that the secondary operates in flux saturation and the secondary winding resonates with the capacitor in a tuned circuit. As a result of this saturated operating mode, changing the primary or line voltage may change the current but will not vary the flux or the secondary induced voltage. Thus the unit performs a voltage regulating action. A unique characteristic of the ferro-resonant regulator is its ability to reduce normal-mode impulses. Since its regulating capability is based on driving the secondary winding into saturation, transients and noise bursts are clipped.

(a) The basic ferro-resonant transformer puts out a high harmonic content squarewave, not suitable for supplying sensitive electronic loads. A properly selected neutralizing winding cancels out most of the harmonic content of the output voltage and yields a satisfactory low-distortion sinewave.

(b) The ferro-resonant regulator has a response time of about 25 milliseconds or 1.5 cycles, good reliability, minimal maintenance requirements, reasonable cost, good normal-mode impulse attenuation, and good regulation. Because of the tuned circuit on the output, it is sensitive to frequency variations (1 percent frequency change causes 1.5 percent output voltage change), but this is not much of a problem with tight utility network frequency control. More important are its high output impedance (again up to 30 percent of load impedance), sensitivity to both leading and lagging load power factors, and low efficiency at partial loads. Efficiency is about 90 percent at rated load, but since the unit wastes about 10 percent of rated load regardless of what load level it is operating at, efficiency drops with load. This, in turn, results in heat dissipation and the generation of audible noise.

(c) In addition, ferro-resonant regulators have poor capacity for handling momentary overloads such as might be caused by high motor starting current, and output voltage collapses at somewhere about 150 percent of full load. Oversizing is not the whole answer to this problem, since this causes reduced efficiency and increased heat dissipation. In summary, the ferro-resonant regulator is useful in small systems that do not contain large motors.

(7) The last type of line voltage regulator to be looked at here is the electronic tap-switching autotransformer. With this unit the proper triac (or back-to-back silicon controlled rectifier [SCR]) is energized depending on whether the power line voltage must be increased or decreased. Voltage correction occurs in discrete steps rather than continuously. Resolution depends on the closeness of the taps, and switching impulses are minimized by changing taps when the line voltage is near a zero crossing.

(a) The electronic tap-switching transformer has many good features. Response time is fast at about 0.5 cycles or 10 milliseconds, regulation is good, output impedance is in the range of 5 percent of load impedance, efficiency is high at about 95 percent, and the units are insensitive to load power factor and load unbalance.

(b) The disadvantages are a somewhat high cost and slightly poorer reliability when compared to the more rugged units.

(c) This type of regulator is popular and widely used in the medium sizes of 3 kVA and up.

e. Line conditioners combine the functions of isolation transformers and line voltage regulators and thus both attenuate impulses and regulate output voltage. For this reason, a line conditioner can protect against the principal types of power line disturbances except for voltage dropouts and line interruptions. It is possible to create a line conditioner by placing separate voltage regulators and isolation transformers in series. Properly matching the two can be tricky, and the package is bulkier and generally more expensive than using a single unit designed to perform the total line conditioner function.

(1) There are basically two types of packaged line conditioners on the market, regulating line conditioners and enhanced isolation transformer line conditioners. The first uses an

improved ferro-resonant transformer voltage regulator, while the second includes an electronic tap-switching voltage regulator in conjunction with a high quality isolation transformer.

(2) The ferro-resonant transformer line conditioner is more popular, being lower priced and highly reliable. The box and Faraday shields around the primary and compensating windings give it essentially the characteristics of a high quality isolation transformer in series with a ferro-resonant voltage regulator. The expected normal-mode impulse attenuation from the saturated operation of the ferro-resonant transformer, plus the electrostatic shields, make this line conditioner a good attenuator of both common-mode and normal-mode impulses.

(3) A typical high quality line conditioner should regulate output voltage to within ±4 percent of nominal for ac input power line voltage changes from –20 percent to +10 percent. Total harmonic distortion (THD) will be less than 5 percent, and both types of impulses should be attenuated up to 120 dB. Other features may include electromagnetic interference/radio frequency interference (EMI/RFI) noise filtering and quality transient voltage surge suppression on the output of the line conditioner as almost all line conditioners are intended to serve multiple loads.

f. M-G sets consist of a motor driving an ac generator or alternator so that the load is completely electrically isolated from the power line. In the past, in some cases dc or induction drive motors were used requiring close speed control to maintain stable frequency to the load. The tendency nowadays is to use synduction or synchronous motors. The synduction motor resembles an induction motor but runs at synchronous speed. With either of these unit types, alternator speed and thus frequency to the load is as stable as power line frequency. M-G sets have been widely used to supply 415 hertz power to the mainframe computers which require this frequency, but recently there has been a substantial shift to the use of solid-state inverters.

(1) M-G sets shield the load from impulses and from voltage sags and swells. For substantial power line voltage changes of ±20 percent or more, voltage to the load is still maintained at ±1 percent of nominal. The unique feature of the M-G is its ability to bridge severe short-term sags or voltage dropouts. The rotational momentum of the rotating elements permits the M-G to span dropouts of up to about 300 milliseconds or 0.3 seconds, the type that cause lights to flicker and plays havoc with digital circuitry. This period can be extended by adding inertia via a flywheel.

(2) The problems with M-G sets are mostly on the output or load side. Very high alternator output impedance can cause substantial voltage dips in response to sudden load changes such as result from large inrush motor starting current, and response to load changes is sluggish in the range of 0.25 to 0.5 seconds. Also, the drive motor may overheat under long-term brownout or low line voltage conditions.

(3) The cost of a M-G set is somewhat more than for a functionally equivalent line conditioner. Also, M-G efficiency is relatively low at about 80 percent, so that electrical energy costs over its lifetime may be substantial. Heat dissipation, weight and bulk, and the potential for annoying audible noise are factors which must be considered in M-G installation. The use of rotating field exciters has eliminated the need for slip rings, with the consequent brush inspection and replacement, but as with any rotating equipment, bearings must be inspected and periodically replaced.

g. If continuous operation is necessary during a line voltage interruption lasting more than a half second or so, then an UPS is required. The basic UPS consists of a rectifier/battery charger, battery bank, and inverter. The rectifier/battery charger takes ac line power of the proper voltage and frequency and generates dc power. The battery bank takes the place of the rectified dc power source if line power fails. The inverter with suitable filtering converts the dc power back into a sinusoidal wave form. UPS systems are complex, expensive, have high output impedance, and frequently require special installation facilities and increased air-conditioning capacity to dissipate the heat. The proper UPS will protect the load equipment from all types of power line disturbances.

(1) The size of the battery bank determines the length of time the inverter will supply normal power to the load. For a large computer installation this time is usually about 15 to 20 minutes, since this is the length of time the computer will operate without air conditioning before the high-temperature trip causes shutdown. An alarm is activated when 5 minutes of battery time remains to permit orderly shutdown. If the load equipment does not require special air conditioning (most process control systems and medical electronics, for example) then it is practical to size the battery bank to cover more extended outages. In this situation, up to an hour of running time is not uncommon and much longer periods are possible.

(2) There are various ways of employing a UPS. The specific configuration to be used is largely dependent upon the reliability of power required by the load.

(a) Continuous mode describes the configuration whereby the load power is always obtained from the UPS except during UPS failure or periods of required maintenance. In this case, the load is manually switched to the raw power line via the maintenance bypass line, causing substantial discontinuity in load operation.

(b) In the forward-transfer mode, the load is normally supplied from the utility power line and the UPS idles. When power fails, the load is automatically transferred to the UPS. In normal operation with this configuration there is no load protection from power line disturbances, except for severe sags and voltage outages, unless other load protection is installed in the utility power line. This tends to defeat the major objective of the UPS.

(c) More popular is the reverse-transfer mode configuration. Here, the load is normally supplied by the UPS and is automatically switched to the utility power line only when the UPS malfunctions. This mode provides maximum benefit from the UPS.

(d) If more extended protection is required, further backup via an engine-driven generator must be added. Here, battery time is usually only about 5 minutes – long enough to get the engine-driven generator up and synchronized with inverter output. Of course, such an installation is very expensive and requires special facilities and substantial maintenance. It should only be considered if extended power outages are frequent and continuity is critical.

(e) For very critical situations there are other configurations that can be considered, including double- and triple-redundant UPS systems backed up by multiple engine-drive generators.

(3) An especially sensitive element, in terms of continuity of service, is the type of automatic transfer switch, which is used. The electro-mechanical transfer switch is actuated when the sensed output voltage to the load drops below 94 percent of nominal. However, sense and switch time ranges from 20 to 50 milliseconds. This time delay will cause most sensitive load equipment to severely malfunction or even shut down. The static transfer switch is much faster. It switches upon sensing a failure in inverter input circuitry, a drop in load voltage to 94

percent of nominal, or overload on the inverter exceeding 130 percent of full load. The sense and switch time is only about 4 milliseconds, so there is a good chance the load's dc power supply will ride right through this short delay and the load will see no discontinuity. Of course, in all transfer situations inverter output must be phased with the power line.

(4) Several different types of inverters used in the UPS system are available. The type that is included in a UPS depends to some extent on the power level requirements for the UPS and on the particular tendencies of the supplier.

(a) The pulse-width-modulation inverter incorporates two inverters, which regulate by varying the pulse width and yield an output, which closely resembles a sinewave. This reduces filter requirements and provides good voltage regulation and response times in the range of 100 milliseconds. However, the extra inverter and feedback networks make this inverter complex and expensive, and it is usually used only at power levels over 50 kVA.

(b) The most popular inverter type in the smaller size ranges is the ferro-resonant unit. It consists of an oscillator, which controls the SCR switches, a ferro-resonant transformer, and a harmonic filter. Its saturated operation produces a regulated output voltage and current limiting, so complex voltage and current feedback networks are not required. Efficiency varies from 50 to 88 percent depending on load level, and response time is about 20 milliseconds. The simplicity of this inverter leads to relatively low cost.

(c) SCRs are used in the inverter section of most large UPS products. A SCR is a semiconductor device with unique properties. It can serve as a rectifier and as a static latching switch. It can handle more power (both voltage and current) than typical transistors, under both continuous and surge conditions. It is the most rugged semiconductor available, and in most cases, can handle more watts per dollar than other types of semiconductors. The SCR serves as an on-off switch. The SCR can be turned on by a momentary application of control current to the gate, while transistors require a continuous on signal. The SCR can be turned on in about 1 microsecond, and static switch sections turned off in 10 to 40 microseconds. The SCR is ideal for rectifier UPS products, but has disadvantages when applied to inverter sections.

(d) In recent years manufacturers have been changing over to transistorized inverters in their UPS products. A transistor permits current to flow through a circuit when the base drive of the transistor receives an electrical signal. Transistors are not latching devices, so they can be turned off by simply removing the base drive signal. To minimize switching losses, however, special drive circuits are required to turn the devices off quickly. Transistors also experience saturation losses during the conduction stage of the cycle. A transistor is considered efficient if it has high "gain" – when relatively small amounts of drive current applied to the base permit a comparatively large current to flow in the collector emitter circuit.

(e) Bipolar transistors produce gain by current conduction. A current applied to the base causes a proportional current to flow in the collector/emitter. A special type of bipolar transistor is called a Darlington, which consists of two transistors linked together. The collector/emitter of the first transistor is used to activate the base drive of the second. Darlingtons have a higher gain than a single bipolar and are easier to control. The disadvantage is that they have higher saturation losses and require special drive circuits to minimize switching losses.

(f) Field-effect transistors (FETs) work differently than bipolars. They do not inject current into the base. Instead, they conduct when they sense a voltage on the gate. This means that relatively little power is consumed in the gate drive. However, the power-conducting portion

has a relatively high resistance. This creates excessive losses and lower efficiency, making it unsuitable for use in large UPS products.

(g) Insulated gate bipolar transistors (IGBTs) combine the best of conventional bipolar transistors and FETs. Like FETs, they only require a voltage across the base in order to conduct. However, like conventional bipolars, they are efficient conductors of current through their collector/emitters. IGBTs are the preferred transistors for UPS applications. They are significantly more efficient and are easier to control than any other power semiconductors. IGBTs are commonly available for UPS applications up to 750 kVA without paralleling devices. Larger devices are available, but have not achieved as much market penetration.

(5) The battery charger/rectifier system operates in a constant-current mode during the initial charge period, automatically switching to a constant-voltage mode towards the end of the charge cycle. This gives maximum battery life consistent with fast recharge, and prevents excessive battery outgassing and water consumption. The charger provides a float voltage level for maintaining the normal battery charge, and sometimes, a periodic higher voltage to equalize certain types of batteries. There are seve ral different types of batteries generally selected for UPS applications. The most common types break down into two technologies: lead acid and nickel cadmium (NICAD). Lead-acid batteries are further broken down into two types: lead-acid/calcium and lead-acid/antimony. Lead-acid calcium batteries can be divided into two categories, wet cell (or flooded) and valve-regulated lead acid (VRLA) sometimes mistakenly referred to as maintenance-free.

(a) The sealed VRLA lead-calcium battery uses either a gelled electrolyte design (GELL), or an absorbent glass mat (AGM) design, does not require the addition of water, and has no problems with outgassing or corrosion. This type is used when the batteries are integral to small UPS systems, and where the batteries must be placed in occupied areas. Their big disadvantage is a limited life span of about five years under optimum conditions. Conventional wet cell lead-calcium batteries are the preferred type in most UPS systems. Watering and terminal cleaning are required only about every six months and manufacturer's warranties are for up to 20 years. They do outgas hydrogen under charge conditions and must be placed in a secure, ventilated area.

(1) The AGM design uses a very fine glass filament matted together and wrapped around the battery plates. This glass mat serves two purposes. Through capillary action, the acid electrolyte is drawn up between the plates with the mat acting as the immobilizing agent. The glass mat is not 100 percent saturated; thus there are small openings between the glass filaments. These openings allow oxygen, which is generated on the positive plate during the final stages of charging to migrate to the negative plate and through chemical reaction, convert back to water, conserving the electrolyte.

(2) The GELL uses a different approach by adding silica to the electrolyte. This mixture will form a gell compound once the battery has formed. After set-up, the gell will have many cracks in it. These cracks are essential to allow for the oxygen exchange between the negative and positive plates. Once in contact, the same chemical reaction occurs as in the AGM design.

(b) Lead-antimony batteries are the traditional lead-acid units. Their performance is equivalent to that of the lead-calcium batteries, but they require maintenance every three months and life is only about one half that of the lead-calcium units. To retain their capacity, lead-antimony batteries require monthly equalize charging.

(c) NICAD batteries are the most expensive of the various types. Their advantages lie in small size and weight for a given capacity and excellent high and low temperature properties. Life is long, nearly that of a conventional lead-calcium battery, and a six-month maintenance period is adequate. They do require monthly equalize charging, as well as periodic discharge cycles, to retain their capacity.

(d) All of these batteries, except for the NICAD type, are surprisingly temperature sensitive and should be maintained between 72°F to 82°F for optimum performance and long life. Low temperatures reduce battery capacity and high temperatures shorten life. If batteries are to be exposed to severe temperature swings, the NICAD type should be seriously considered.

h. The magnetic synthesizer is a static electromagnetic (EM) three-phase ac power regenerator. The device, powered from the ac utility line, uses no mechanically moving parts in the generation process, and utilizes no semi-conductor elements in the power path. The output wave form of the device is electromagnetically generated, and is completely isolated and independent of the input in all parameters except two, the phase rotation and the frequency. The output phase rotation of the device is governed by the direction of the input phase rotation, while the output frequency is precisely keyed to the input line frequency. There is no electrical connection between the input and the output of the device. The only power line disturbances not correctable by a magnetic synthesizer are frequency deviations and loss of power, both of which require a UPS to correct. An ideal application for a magnetic synthesizer is in a major urban area where utility networks or loops are fed from multiple substations providing very reliable but otherwise “dirty” power. The improved quality of power results from the synthesis of three-phase 60 hertz voltage wave forms which remain essentially constant in magnitude and shape over a large range of input voltage excursions in both the positive direction (surges) and the negative direction (sags). The device consists solely of saturable iron core reactors and transformers, together with capacitors, and employs the principles of ferro-resonance for its operation.

(1) As long as the core of an inductor is not magnetically saturated, the inductor will support a voltage across the windings. However, as the inductor core approaches saturation, the current through the winding will begin to increase. When the core becomes completely saturated and can absorb no more magnetic flux, tremendous currents will flow through the winding, and the voltage across the winding will approach zero. In essence, the device will go from an open-circuit to a short-circuit.

(2) If the voltage across the saturated reactor is now reversed, the core will begin magnetizing in the other direction and will again act as an open-circuit. The inductor will support this reversed voltage until the core becomes saturated in the opposite direction. At this point, the reversed current increases to a maximum and the voltage decreases to a minimum. In standard 60 hertz non-saturating devices, the core flux is oriented in one direction for 1/120 second; but before it can reach the point where the core cannot absorb any more flux, the voltage is reversed, which begins to orient the core flux in the other direction for the next 1/120 second.

(3) The amount of time for the saturation of a reactor core to take place is measured in volt-seconds. The volt-seconds rating for an inductive reactor depends upon the frequency and the voltage desired to be present across the reactor winding before saturation.

(4) A saturating transformer is inherently a non-linear device. It is this non-linearity which makes it valuable in regulating circuits. In a saturating transformer, as in conventional

transformers, production of an output voltage depends upon the changing magnetic flux in the transformer core. But unlike conventional transformers, the saturating transformer is designed for the core to reach saturation after a given number of volt-seconds. Because the flux no longer changes when the core is saturated, there is no voltage output at this time.

(5) The primary waveshape and output power level determining elements of the magnetic synthesizing power conditioner are saturating transformers. In order to obtain the desired outputs from these transformers, energy must be injected into the devices. In the magnetic synthesizer power conditioner, energy is introduced through line chokes into the primary windings of the saturating transformer elements. The line chokes are designed to pass the electrical energy from the input lines, while blocking the waveshape and voltage level information. The chokes act as current sources and buffers for the saturating transformer elements. The primary windings are duplicates of the regulated windings of the secondary. Because the primary windings are wound on top of the secondaries and are isolated from them, there is introduced the ability to reject common-mode noise. The primary-over-secondary arrangement also provides a fail-safe feature. A broken connection at any point will not cause the voltage to rise toward infinity at the load. There is no high-voltage failure mode in this device.

(a) Six interconnected saturating transformers are utilized for power wave form synthesis in the power conditioner. At any particular time during operation, one of these cores is unsaturated while the other five are saturated in directions specified by the interconnection configuration. When the one core finally becomes saturated, the voltage across it collapses and it becomes a conductor. That process causes reversal of the voltage across one of the remaining five cores, which then goes out of its present saturated state and begins building toward saturation in the other direction. When the core reaches saturation in the other direction, it will then reverse the voltage across yet another core.

(b) The sequence of saturation and voltage reversals among the transformers is determined by the transformer interconnection configuration and by the phase sequence of the driving circuit. The process continues as long as the power conditioning device is in operation. During the time that a transformer core is unsaturated, there is voltage present in the transformer interconnecting circuit of the power conditioning device. Therefore, sequencing of the transformers will produce a constant series of voltage pulses on the interconnecting circuit. The parameters of each pulse are determined by the volt-seconds design of the corresponding core.

(c) The three-phase sine waveforms which are produced by the design and interconnection of the transformers in the power synthesizing device contain less than 3 percent THD. Because each of the wave forms is produced by a saturated element, both the shape and amplitude are stable. Thus, the transformer configuration becomes a source which dictates the voltage level and waveshape of the resulting output. Close voltage regulation is maintained and clean waveshape is assured, each independently of the input line conditions.

i. High quality transient voltage surge suppressors (TVSSs) are available to protect ac systems at all distribution voltage levels. The TVSSs have let-through voltages much lower than basic lightning arresters and are designed for facility and sensitive equipment protection. TVSSs are designed to handle much higher speed transients than lightning arresters.

(1) Underwriter's Laboratory (UL) Standard 1449, Standard for Transient Voltage Surge Suppressors, categorizes TVSS into three types: (1) Direct plug-in TVSS devices incorporate integral blades for connection directly to electrical outlets by consumers wherever point-of-use surge protection is desired. (2) Cord connected TVSS devices have a power supply cord

terminating in an attachment plug for connection to nearby electrical outlets by consumers, wherever area of use is desired by the end user. (3) Permanently connected TVSS devices are equipped with terminals or leads that are hard wired by qualified personnel into the building's electrical service entrance and distribution system.

(2) UL recently revised UL Standard 1449, Second Edition, August 15, 1996, for permanently connected TVSS devices to increase the test duty cycle a TVSS must pass. The measured limiting voltage test was previously known as the "transient voltage surge test." This test assigns a suppression voltage rating, or let-through voltage, to a product under test. The first and last test surge current magnitude used to benchmark and measure the TVSS capability has been reduced from 3000 A to 500 A. While the duty cycle part of the test has been reduced in number of impulses from 24 to 20, the current magnitude has been increased from 750 A to 3000 A. The benefit of this change is that the TVSS under test is now subjected to a more strenuous duty cycle test than with the previous version of the test. A wide variety of additional tests have been included in the revised UL 1449, including testing of components (capacitor endurance test), enclosure integrity tests (enclosure impact test, crushing test, mold stress-relief distortion test, mounting hole barrier test, and adequacy of mounting test), as well as manufacturing and production line testing.

3-5. Power distribution systems

Power distribution systems, otherwise called movable power systems or computer power centers, are sometimes confused with load protective equipment. The purpose of a power distribution system is to provide convenience in distributing power to computer system elements, to avoid some electrical contractor expenses, and possibly to obain a better job, particularly if the contractor is not experienced in computer system installation. Power distribution systems are made by some computer suppliers and independents, but they do not provide any protection against power line disturbances unless specially equipped to do so. However, such a UL listed system should certainly be considered for complex computer installations since it can provide proper wiring and grounding, monitoring of key power system variables, and other features which will assure that good installation practices have been followed.